Renewable and Sustainable Energy Reviews 15 (2011) 4030–4041

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Recent developments in microgrids and example cases around the world—A review

Taha Selim Ustun*, Cagil Ozansoy, Aladin Zayegh

School of Engineering and Science, Victoria University, Melbourne, Australia

ARTICLE INFO

Article history:
Received 7 January 2011
Accepted 5 July 2011
Available online 21 August 2011

Keywords:
Distributed generation
IEEE Standard 1547
Microgrid control
Microgrid management system
Protection
Renewable energy

ABSTRACT

Climate change concerns due to the rising amounts of the carbon gas in the atmosphere have in the last decade or so initiated a fast pace of technological advances in the renewable energy industry. Such developments in technology and the move towards cleaner sources of energy have made distributed generation (DG) from renewable resources more desirable. However, it is a known fact that rising penetrations of DG can have adverse impacts on the grid structure and its operation. The microgrid concept is a solution proposed to control the impact of DG and make conventional grids more suitable for large scale deployments of DG. Covering many aspects of the power systems and power electronics fields, microgrids have become a very popular research field. This paper reviews the background and the concept of a microgrid, the current status of the literature, on-going research projects, and the relevant standards. It also presents a review of the microgrid pilot projects around the world in further detail and discusses the potential avenues for further research.

Contents

1. Introduction

The prominence of generating electric power in very large steam-powered central power stations seems to have ended. The increased concerns for the environmental impacts of centralized coal-fired generation, most importantly those that relate to high CO_2 emissions, are the main factors driving the transition towards small-scale decentralized generation of power. Decentralized (distributed) generation of electricity most favorably occurs from renewable sources that are located on the distribution system close to the point of consumption. Governments and industries all

* Corresponding author. Tel.: +61 3 9919 5046; fax: +61 3 9919 4908.
E-mail address: tahaselim.ustun@live.vu.edu.au (T.S. Ustun).

1364-0321/$ – see front matter. Crown Copyright © 2011 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2011.07.033

around the world are increasingly looking for ways to reduce the greenhouse emissions from their operations with a major focus on the use and installation of sustainable distributed energy systems [1].

The need for far more efficient electricity management systems has given rise to the development of innovative technologies and groundbreaking ideas in power generation and transmission. The trend is to increase the share of DG in the electricity supply. DG may also comprise renewable energy (RE) systems such as solar, wind and wave, which are promising cleaner technologies leading to reductions in greenhouse gas emissions and in effect aiding in the remedy of the global warming problem [2]. Consequently, governments and energy regulation authorities worldwide are encouraging more deployments of RE based distributed generator systems (DGS). However, higher penetration of micro-sources, i.e. small scale PV panels, wind turbines, and diesel generators into the grid changes the traditional "radial" structure of the grid. This revolutionary change in the structure triggers many problems which were previously unknown to the grid operators and power engineers [3]. There are now various microsources at different penetration levels in the grid and this new structure invalidates the traditional power flow control methods. Moreover, DGS also make contributions to the fault currents around the network. Hence, in case of a fault, the transient characteristics of the network become completely different [4]. These are only a few of the issues that have arisen in relation with the revolutionary changes occurring in the grids and the way they are operated.

There are still many technical challenges that must be overcome so that DGS can be cost-effectively, efficiently and reliably integrated into existing electric power systems. Existing distribution systems are not designed for significant penetration of DG. Distribution systems were traditionally designed with the assumption of a passive network. The interconnection of decentralized renewable energy generation systems to such networks inevitably changes the characteristics of the system and presents key technical challenges such as circuit protection coordination, power quality, reliability, and stability issues that must be overcome. Controlling a huge number of geographically dispersed DGS in a large network is a daunting challenge for the safe, reliable, and effective operation of the network.

The search for alternative energy sources and more efficient utilization of the energy as a means of tackling the global warming concerns will require fundamental changes in the electrical engineering (EE) field explicitly in relation to the matters associated with the Transmission and Distribution (T&D) of this renewable electricity. Although T&D grids have been around for many decades, DG and RE concepts have recently become irreversibly popular. As a result, many research and development needs have evolved as a necessity to enable the scaling up of the implementation and uptake of renewable energy systems giving them recognition and equal status in energy sector investment processes.

Microgrids, which are small entities in a power system network, are capable of coordinating and managing DGS in a more decentralized way thus reducing the need for the centralized coordination and management of such systems [5]. This is highly recommended in [5], where it is claimed that such a scheme would permit DGS to provide their full benefits. Yet, there are still many research and development needs associated with the microgrids. [5,6]

This paper presents a detailed review of the literature with regard to microgrids by outlining the existing knowledge as well as the problems and challenges being encountered. It also provides an overview of the current research and development work being carried out all over the world. It gives an insight into some real-life implementations of microgrids. Finally, it focuses on knowledge gaps yet to be addressed and possible future work in this field of power/electrical engineering.

2. The microgrid concept

A microgrid is a new concept which refers to a small-scale power system with a cluster of loads and distributed generators operating together with energy management, control and protection devices and associated software. Such devices include the flexible AC transmission system (FACTS) control devices such as power flow controllers and voltage regulators as well as protective relays and circuit breakers [7]. In other words, a microgrid is a collection of loads and microgenerators along with some local storage and behaves just like a model-citizen from grid side thanks to intelligent control [8]. This means, although a microgrid is itself composed of many generators and loads, it appears as a net load or a net generator to the broader grid with well-behaved characteristics [9]. A sample microgrid architecture is shown in Fig. 1.

As shown in Fig. 1, the microgrid is a very versatile concept as it can accommodate various types of the micro generators (wind turbine, photovoltaic (PV) array, diesel generator, and wave generator), local storage elements (capacitors, flywheel) and loads. A distributed generator might be a diesel generator (DG4) which can be coupled to the grid directly, or a PV array which needs direct current (DC)/alternating current (AC) inverter interface (DG2, DG3) or an asynchronous wind turbine (DG1) which requires AC–DC–AC inversion for proper grid connection. Similarly, the storage devices used in the system may or may not require an inverter interface as in the case of capacitor banks and flywheel, respectively.

A microgrid can be a DC [10], AC or even a high frequency AC grid [11]. It can be a single or a three phase system or it may be connected to low voltage or medium power distribution networks [7]. Furthermore, a microgrid could be operating in either grid connected or islanded operation mode. For each operating mode operational requirements are different and distinct control schemes are required.

The groundbreaking feature of a microgrid is its ability to operate "autonomously" when there is a power outage in the main grid. This operation mode is called islanded operation since the microgrid disconnects from the grid and becomes an island with local generators and loads. In this way, the consumers may receive continuous service even when there is power outage in the grid due to a fault or maintenance. Moreover, if there are voltage sags, frequency drops, or faults in the main grid then the microgrid can be easily disconnected, i.e. islanded from the rest of the grid and the users can be isolated from those problems. In this way, microgrids not only help in providing uninterrupted service but also contribute to the maintaining service quality.

The motivation behind using microgrids is to divide the enormous conventional utility network into smaller and more easily operable grids. These smaller electrical networks will manage distributed generators, loads, storage and protection devices in their own grid. Provided that each microgrid is operating as a model citizen, i.e. either as a load receiving power with acceptable electrical characteristics or as a power supply supplying power with acceptable electrical characteristics, then the overall utility grid can be operated properly. It is a well-known fact that higher penetration levels of distributed generators, especially those that require power electronics (PE) interface, alter the grid structure and jeopardize safe and reliable operation. The microgrid concept is introduced to manage these generators in smaller quantities rather than trying to tackle the whole network in a holistic manner. In this way, more distributed generators can be employed in the grid and side-effects on the grid operation can be eliminated.

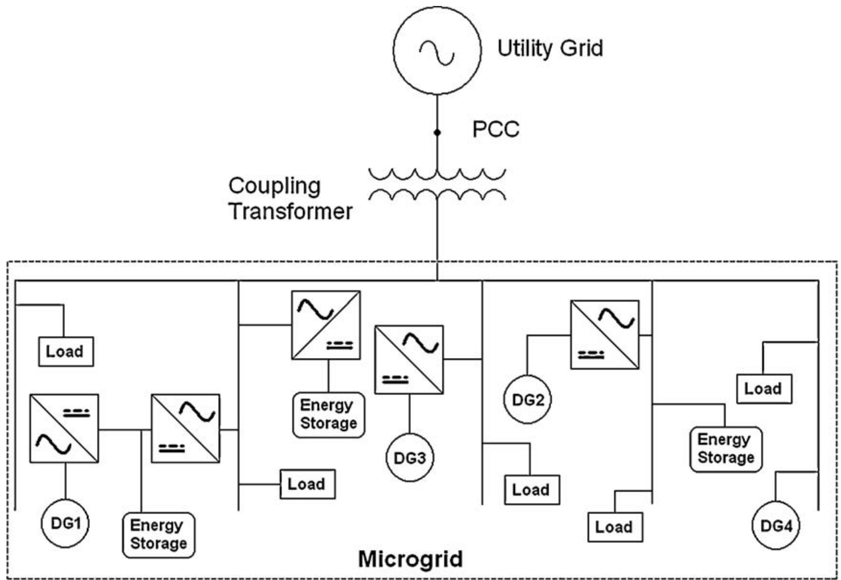

Fig. 1. A sample microgrid architecture.

3. Current status of literature and ongoing research

Distributed generators and storage devices almost always require a PE interface for a proper connection to the grid. Accordingly, all research on PE devices such as inverter control and storage can therefore be linked to the microgrid research field. For better operation and control, PE devices such as insulated gate bipolar transistors (IGBTs) or thyristors with higher current/voltage ratings are required. References [12,13] discuss the research projects that are being carried out to accomplish these objectives. Energy storage is an indispensible part of microgrids for storing excess energy, supplying power in case of shortages, and for preventing voltage sags. For a better operation; energy storage devices with higher efficiencies, longer lifetimes along with faster charging and slower discharging characteristics are desired. Projects with a focus on energy storage matters are outlined in [14].

The most promising one of the new generation batteries is the NAS (sodium–sulfur) battery. Although it needs to be maintained at high temperatures, it has advantages when compared with other types of batteries. Table 1 [15] shows that a NAS battery, when compared with other battery types, has substantially a higher energy density, a fair efficiency and no self discharge. These characteristics of NAS make it very appealing and hence it is being deployed by companies operating in the RE sector in Japan and in the United States (U.S.).

Another innovative energy storage system is being developed by the RAPS Pty Ltd. which is based on high purity graphite blocks. These blocks are heated up with energy received from solar panels, wind generators or the grid for later use. This energy may then be used to produce steam through embedded heat exchangers and converted back to electricity with steam turbine generators [16]. According to the inventor company, the storage capacity of high purity graphite ranges from around 300 kWh (thermal) per ton at a storage temperature of 750 °C to around 1000 kWh (thermal) per ton at 1800 °C [17]. There are pilot deployments in Silverwater and King Island, Australia.

The research and development (R&D) work being undertaken at the device level is very comprehensive and the literature can be referred to. The main focus of this article will be three main sub-topics of microgrid research: control, protection and microgrid management systems.

3.1. Control

The controller capabilities of a microgrid are one of the most crucial elements in determining the introduction of this new concept to the utility and its wide acceptance. Depending on the type and depth of the penetration of distributed energy resource (DER) units, load characteristics and power quality constraints of a microgrid can be significantly and even conceptually different than those of the conventional power systems [18]. Market participation strategies, the required control and operational strategies can also be added to this list. This is due to the fact that the characteristics of DGS are much different than conventional synchronized motors. They rely on intermittent resources in the system which cannot be controlled or estimated. Hence, a microgrid is a dynamic entity and DGS might connect/disconnect while the microgrid is in operation.

The main objective of control systems in microgrids is to continuously supply power to the loads despite the changes in the system. A microgrid may be operating in grid-connected mode and gets islanded due to a fault. One or more DG units may connect to/disconnect from the grid, or there might even be significant changes in the amount of power demanded by the loads. Under all these circumstances, the microgrid control shall ensure that power is supplied to the loads with acceptable voltage and frequency characteristics. Since there are two distinct operation modes of a microgrid, control schemes are designed for two distinct phases. Table 2 [18] shows the control strategies of DG in a microgrid. When there is grid connection, grid-following controls are employed. On the other hand, in islanded operation, when a grid needs to be formed, grid-forming controls are used.

In the grid-following mode, the frequency and voltage values are dictated by the utility grid and DG units are operated to follow these set values. The non-interactive control method strives to harvest the maximum power available through maximum power point tracking (MPPT), or a predetermined amount of power whereas the interactive control method is used for real and reactive power support depending on the system and the loads. The former method is suitable for solar panels and wind generators where the energy resources are inconsistent and unreliable. The latter method is implemented in DGs such as diesel generators or distributed storage devices which can supply energy continuously. A microgrid may incorporate both of these control methods for different types of DGs.

Table 1
Batteries used for distributed energy storage.

	Unit	NAS	Redox flow	Lead	ZincBr
Voltage	V	2.08	1.4	2	1.8
Ideal energy density	Wh/kg	780	100	110	430
	Wh/l	1000	120	220	600
Efficiency	% DC	85	80	85	80
Temperature	°C	280–350	40–80	5–50	20–50
Auxiliaries	–	Heater	Pump	Water	Pump
Self Discharge	–	No	Yes	Yes	Yes

Table 2
Control strategies for DG coupling inverters in MG.

	Grid-following	Grid-forming
Non-interactive control methods	Power export (may be with MPPT)	*V–f* control
Interactive control methods	P and Q support	Load sharing

Fig. 4. Control levels of the microgrid [70].

When microgrid operates in islanded mode, a similar two-way approach is used. Some large DGs are operated with voltage and frequency (*V–f*) control to keep these values constant in the islanded microgrid. If this is achieved with a number of DGs, then the rest of them will be operated in the load sharing mode to share the loads in the system. In this fashion, the microgrid operates within acceptable voltage/frequency limits and the loads are supplied with the required power.

The most popular control scheme employed for load sharing is droop control since it realizes automatic load sharing in a microgrid without any central control mechanism or communication between DGs [19,20]. This feature shines when the microgrid is working in islanded mode where droop control solves the control problem [21]. In fact, it has been demonstrated that by imitating the generator-turbine-governor units, drooping characteristics can be successfully applied to inverters working in an isolated AC system. [22]. Of the two possible generation modes, *V–f* and, real and reactive power (*P–Q*) droops, the latter is more preferable by producers whereas the former is needed to form a grid, especially in islanded microgrids [23]. This is yet another challenge for microgrid operation where there is poor market organization. To better understand the theory behind it, please consider the power flow equations given in (1) and (2):

$$U_{rec} \times \sin\delta = \frac{X \times P - R \times Q}{U_{sen}} \tag{1}$$

$$U_{sen} - U_{rec} \times \cos\delta = \frac{R \times P + X \times Q}{U_{sen}} \tag{2}$$

where X, line reactance; R, line resistance; P, real power; Q, reactive power; U_{sen}, sending end voltage magnitude; U_{rec}, receiving end voltage magnitude and δ, phase difference between sending and receiving ends.

For high voltage lines $X \gg R$, R may be neglected, and δ is very small. So assumptions can be made that $\sin\delta = \delta$ and $\cos\delta = 1$. The equations can then be rewritten as follows:

$$\delta = \frac{X \times P}{U_{sen} \times U_{rec}} \tag{3}$$

$$U_{sen} - U_{rec} = \frac{X \times Q}{U_{sen}} \tag{4}$$

It can be seen from (3) and (4) that the power angle mostly depends on the real power whereas the voltage difference mostly depends on reactive power. In other words, by controlling P and Q, the frequency and the voltage of the grid might be set.

$$f - f_0 = -k_p(P - P_0) \tag{5}$$

$$U_{sen} - U_0 = -k_q(Q - Q_0) \tag{6}$$

where f, frequency; f_0, rated frequency; U_0, rated grid voltage; P_0, Q_0, set real and reactive power of the inverter.

The infamous droop regulation Eqs. (5) and (6) are obtained by associating a permissible error on the voltage and frequency values with real and reactive power values. When there is a variation in the frequency or the voltage value, the DGs adjust their real and reactive output values accordingly. The adjustment should be done and the power mismatch should be recovered immediately to maintain the system frequency. Consequently, storage devices are needed for a successful droop control implementation [21,24]. The power sharing of the generators are mostly indirectly proportional to their capacities. The load sharing coefficient m_P is based on an equitable load share in the form:

$$m_{P1} \times P_1 = m_{P2} \times P_2 = m_{Pi} \times P_i = \text{constant}(k), \tag{7}$$

where P_i is the rated output power of ith DG [25]. It is worthy to note that this scheduling scheme does not take technical or financial aspects into account. That is to say, DG's ability to provide sufficient level of reserves or the economical outcome is not considered in determining new droop operating points. In tackling this issue, [26] acknowledges the economic importance of selective sharing amongst DGs and proposes using four different droop coefficients based on production cost or available reserves. Although this improves the droop performance, it has stability concerns since the increase of droop coefficients beyond a limit triggers instability [27].

Another shortcoming of droop control presents itself when implemented in low voltage networks. For low voltage wires, $X \gg R$ assumption does not hold [28] and classical droop equations are insufficient. The control system proposed in [29] considers the effect of R and uses improved droop equations. Another improvement presented in [37] is controlling not only the fundamental component of the voltage but also its harmonics. Systems proposed in [25,29,30] have droop control for harmonic components and thus can feed non-linear loads. In order to address the versatile nature of microgrids, the central controller in [31] calculates droop lines for every different condition, shown in Fig. 2, and updates them. This gives the controller the flexibility it needs to respond varying operation modes.

The conventional droop method employs low-pass filters to calculate average P and Q values, hence it has a slow dynamic response [32]. A wireless controller was proposed in [33] to enhance the dynamic response with integral–derivative term addition. Furthermore, the power sharing is degraded when the sum of output and line impedances are not balanced. This might be solved with interface inductors or with control loops that emulate lossless resistors and reactors as in [34].

There are alternative drooping schemes available in the literature. For example, [35] proposes a control scheme that droops microgrid output voltage with real power (P) and system frequency (f) with reactive power (Q). This is in stark contrast with conventional load sharing schemes [36]. However, this system can only be used for only one voltage source inverter (VSI) and

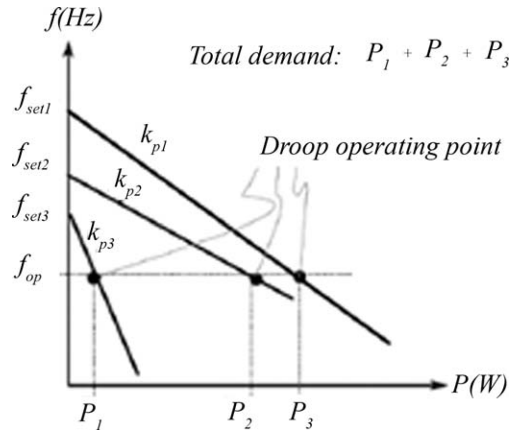

Fig. 2. Different droop lines and operating points in [31].

another scheme called voltage-power droop/frequency-reactive power boost (VPD/FQB) control is proposed in [37]. This scheme also droops the voltage reference against real power output and boosts the frequency with reactive power output. In addition to that, it can be run in parallel with other VSIs and the utility grid itself.

Other controls include controlling resistive output impedance of the inverters and realizing load-sharing with wireless load-sharing controllers [38,39] or running all inverters in grid-following mode even if the microgrid is islanded [40]. The system in [24] has two level control design which implements droop control for system level multiple DG coordination controllers and L1 control theory for device-level inverter controllers. This realizes a more reliable, robust and stable microgrid control.

3.2. Protection

3.2.1. Islanding

Islanding is a situation that occurs when part of a network is disconnected from the utility grid but is still energized by one or more DGs [41]. In conventional distribution networks, in the case of a fault in the transmission system, the distribution network does not receive any power. However, with the introduction of DGs, this presumption is not valid any more [42]. This phenomenon of unintentional islanding may cause some of the following issues:

- Safety issues since a portion of the system remains energized when it is not expected;
- Loss of control over system frequency and voltage levels;
- Insufficient grounding of the islanded network over DG interconnection;
- Out of phase re-closure problems which may damage the equipment [43]

Because of these issues, a DG unit should pass either one of the two anti-islanding standard tests, UL 1741 [44] or IEEE 1547 [45] before it can be installed. Moreover, almost all utilities require DG units to be disconnected from the grid as soon as possible in case of islanding. IEEE 929-1988 standard [46] requires the disconnection of DG units once the microgrid is islanded. The IEEE 1547-2003 standard on the other hand requires all DGs to be shut down after a maximum delay of 2 s once islanding is detected. In order to achieve this, there must be a fast and reliable islanding detection method. There are various kinds of islanding detection methods in the literature which are studied under two sub-headings; remote and local techniques. The local techniques include three types which are: passive, active and hybrid detection methods.

Passive detection methods measure some local parameters such as voltage, frequency, total harmonic distortion [42], rate of change of power signal [47], rate of change of frequency over power. By comparing these values with pre-determined thresholds, islanding is detected. Passive detection methods detect islanding very fast and without disturbing the system. However, should the mismatch be small they become unreliable. The challenge of setting suitable thresholds and the large non-detection zone are the major drawbacks [10] of passive methods.

Active detection methods try to address the shortcomings of passive methods by intentionally introducing perturbations into the system and detecting islanding according to the response of the system [48]. In this way, it is possible to detect islanding even if the power mismatch is very small hence a much smaller non-detection zone. The downside of active methods is that they are not as fast as passive methods and they degrade the power quality with the injected perturbations.

Hybrid detection methods are the combination of passive and active methods. The system is constantly monitored with passive methods and if islanding is suspected by the passive methods then the active methods are implemented. This combines smaller non-detection of active methods whereas unnecessary disturbance in the system is prevented by passive methods [42]. The drawback is long detection time since both of the methods are implemented.

There are communication based approaches to islanding detection with an effort to overcome the problems posed by active and passive detection methods. These methods are based on a direct communication between the utility and DGs in a microgrid [49]. Islanding is caused by opening of a line circuit breaker so it is proposed to use this event to detect islanding and execute necessary protection schemes. Some of the methods that incorporate this principle are [50]: power line carrier (PLC) communications, supervisory control and data acquisition (SCADA), intertripping/disconnection signal. These methods do not suffer from non-detection zones and they do not affect the power quality by de-stabilizing the system. The only set back is the additional cost of communication systems and their reliability. According to [51], PLC communication is a practical, reliable and cost-effective method to realize islanding detection. In this method, a signal is injected to bus bars at substations and DGs operate as long as they receive the signal. Should a tripping occur and the microgrid become islanded, the signal vanishes and DGs are shut down automatically [49].

3.3. Fault current protection

Integration of DGs to the grid and the increasing penetration level changes fault current level and direction in networks [52]. Traditional protection schemes shall be re-designed in order to meet these fundamental changes. Also microgrids have dynamic structures, i.e. several DGs and loads connect/disconnect at any instant, and various operating modes. Fault current levels may vary for all these situations and current protection designs are not sufficient to tackle these issues. Some of the prominent protections issues are: short circuit power, fault current level and direction, device discrimination, reduction in reach of over-current relays, nuisance tripping, protection blinding etc. [53,54].

In conventional power networks, the power flows from higher voltage levels to lower voltage levels. In case of a fault, the short circuit current decreases as the distance from the source increases. However, DGs change these concepts as there may be power flow from the microgrid to the utility if the local generation exceeds local consumption. As Fig. 3 shows the fault current may grow downstream with the contribution of fault currents from DGs. Fault contribution from a single DG may not be large; however the combined effect of several DGs can reach significant levels [55].

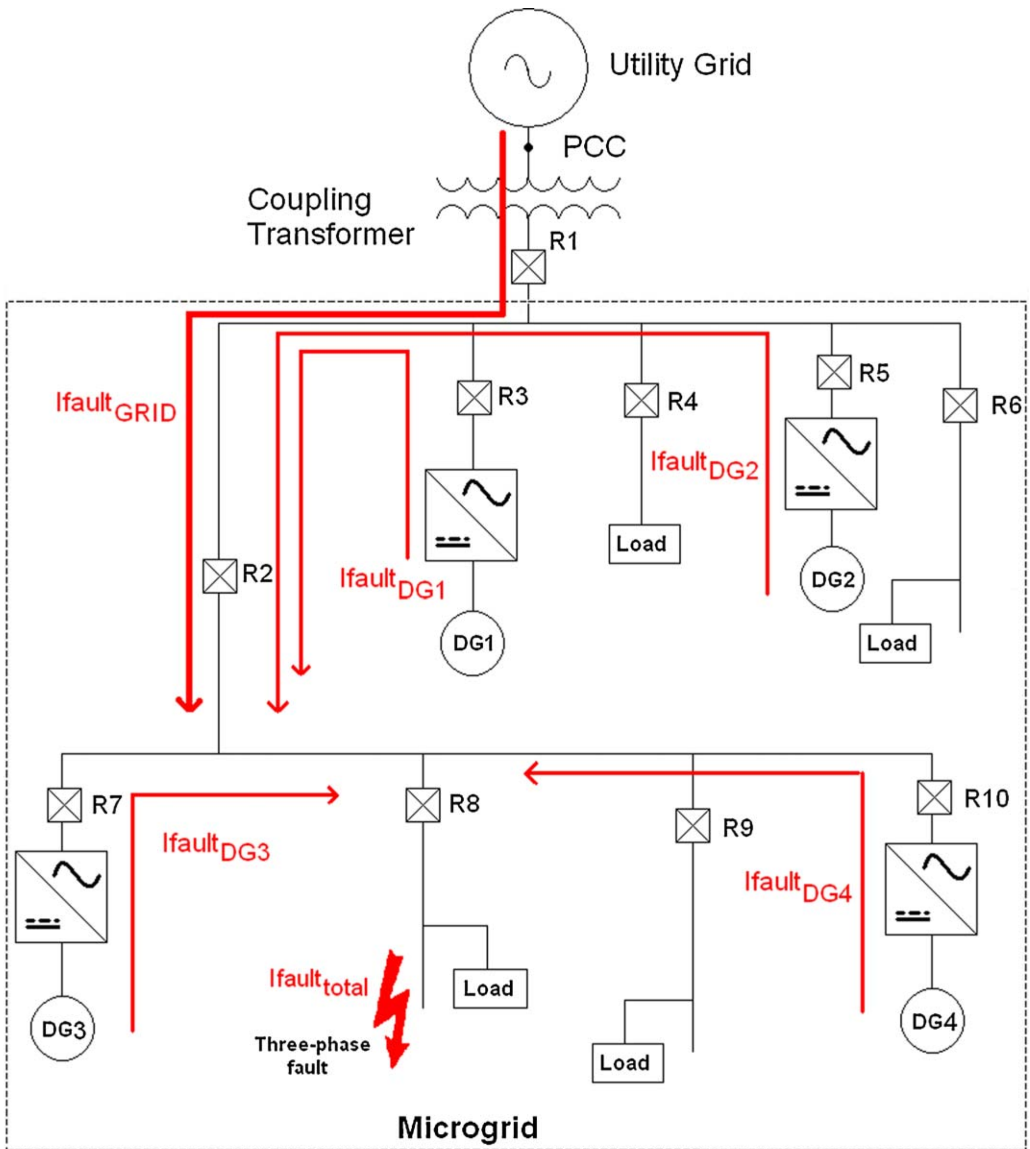

Fig. 3. Grid and DG fault current contribution in MG.

Estimating this contribution is not an easy task as it highly depends on the type of the DG. Another problem is that DGs with PE interface do not supply short circuit currents sufficient enough to trigger protective devices [56]. If the fault current settings of the relays are decreased so that they sense fault currents from inverter-interfaced DGs, then undesired trippings and nuisance trippings will occur due to transients in the system [57]. The position of a fault with respect to DG also affects the operation of protection system. It may be that the relay is only measuring some part of the actual fault current as there may be several fault current paths towards the fault [58].

Moreover, fault currents are different for grid-connected and islanded modes of operation. In the former case, the utility grid contributes to the fault current whereas the latter only includes the fault currents from DGs. In an islanded grid, the storage devices, intermittency of DGs such as solar panels or wind turbines, load types and their power demand affect the fault levels. The new protection system should be dynamic and respond to those changes in the operation conditions. [59]

Furthermore, low voltage systems may have single phase loads which will alter the balanced system parameters. DC microgrids which have simpler connection and more efficient PE interfaces need special attention [60]. Protection of microgrids against over voltages [61] or utility voltage sags [62] are also amongst popular research fields.

There are different solutions proposed in the literature for the issues stated above. The use of anti-islanding frequency relays is proposed in [63]. However, it is not realistic to assume that all relays can be replaced [54], so the method in [64] can be implemented where operating points of relays are calculated with modified particle swarm optimization. In another approach, instead of using relays and circuit breakers blindly, some smart algorithms are implemented to selectively operate relays and isolate the fault [65].

There are more ground-breaking systems which employ a developed communication system to follow the system parameters and carry out necessary calculations [53,59]. Standard communication protocols such as the IEC 61850 might be used in these systems as in [66], however it is of concern that how the new fault currents and fault levels shall be calculated for any change occurring in the system. Current systems use some sort of database or event table to search the current status and take pre-determined precautions

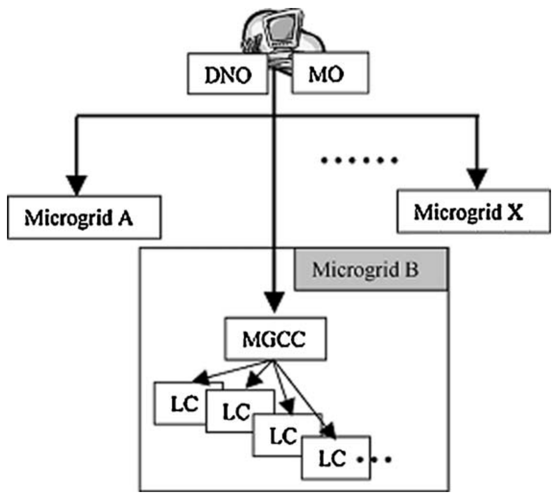

Fig. 4. Control levels of the microgrid [70].

[53,64]. However, since microgrids are designed to accommodate new generators and loads, these schemes are not practical. Some sort of algorithm which manages to adjust the protection scheme to the new state of microgrid is direly needed. Machine learning, artificial intelligence or fuzzy logic algorithms are the trivial candidates as a foundation for such adaptive-automatic microgrid protection schemes. It is also discussed in the literature that having extensive communication networks would make the microgrid more expensive and less reliable. Moreover, in a distributed energy system, components may be located far away which makes communication difficult [27].

3.4. Microgrid energy management system (MEMS)

In order to execute the duties described so far, a microgrid utilizes a microgrid management system. This system ensures that different components of the microgrid are managed to serve towards a certain objective [67]. It typically comprises of three hierarchical levels of control as shown in Fig. 4.

Microgrid central controller (MGCC) acts as an interface between the microgrid and the outside world. It communicates with distribution network operator (DNO) and market operator (MO) and optimizes microgrid operation through local controllers (LCs). It ensures that in a network where more than one microgrid exists, microgrids work in harmony to sustain a reliable and safe operation. LCs are responsible to control components of a microgrid such as distributed generators, storage devices, loads or protection equipment. MGCC manages LCs and updates their operation modes and points in parallel with the events occurring in the network and/or the microgrid. Once the updates are received, LCs mostly behave autonomously until a new instruction is received from MGCC [68]. Based on the decision making scheme, the control systems (also known as supervisory systems [18]) are categorized as centralized and decentralized microgrid control [69].

Centralized control strives to maximize the local production according to market prices. For this to occur, there is a two-way communication between the MGCC and each LC [18]. Starting from this point there is a new concept called virtual power plants (VPPs) where distinct entities inside a microgrid are controlled by a central unit to act as a power plant [71].

Conversely, in decentralized control, the larger part of the decision making is in the hands of LCs. They act in a smart fashion and communicate with each other to increase the revenue and the performance of the microgrid. The most popular way to design this intelligent system, which is composed of smaller less intelligent components, is by using multi-agent systems [70]. Multi-agent systems are already proposed for the protection, stabilization, restoration of large power systems.

There are on-going research projects being carried out to investigate alternative control systems. A control system based on 'Game Theory' is proposed in [72]. In this approach, power electronics based inverters are treated as variable impedance loads and every generator in the microgrid is taken as a player. The stabilization and the control of the system may be achieved through real-time or turn-based games. For different scenarios, different games such as "Maximum Power Game" or "Microgrid Stability Game" can be played. Depending on the level of communication, games might be cooperative and non-cooperative.

In an another study, the "Ant Colony Optimization" algorithm is proposed to solve constraint satisfaction problem for microgrids [73]. Ant colony optimization is a nature-inspired artificial intelligence technique where several ant colonies cooperate to solve a problem. In microgrid applications, distributed generators, storage devices and loads are represented by a variable. The domain of each variable represents the quantized operating points at which the generator or load could be commanded to operate [73]. By stipulating constrains, ants walk on the construction graphs and each variable will be assigned an operating point. The touring of the colonies continue until the solution is attained for each and every variable.

By implementing a central control unit in microgrids, different objectives can be realized. Minimizing system disturbances, maximizing efficiency, meeting power demands from local resources, stabilizing the system are to name a few. This formulation outlines the difficulty of the control task. With competing objectives and highly variable parameters, a real-time power management system which is both robust and flexible is needed.

4. Examples around the world

There are various microgrid implementations or active experiments worldwide to understand the operation of microgrids in a better sense. Different technologies and topologies have been studied for different purposes. Some of the experiments are run for purely R&D purposes whereas others are deployed on islands or isolated/distant grids. Since the microgrid concept is very versatile, the experiment conditions and the objectives have a very wide span.

4.1. European union (EU)

The level of climate change awareness in the EU is very high and there are certain targets that need to be achieved by the member states by 2020. There are various directives passed by the European Parliament such as 2001/77/EC, 2003/30/EC and 2006/32/EC. These directives stipulate that the carbon emissions shall be reduced by certain amounts, the share of renewable energies in the energy market shall be increased and the energy consumption shall be reduced by increasing energy efficiency [74]. Accordingly, there are incentives from the EU and several on-going projects in member states.

The first project funded by the EU was the "Microgrids Project" and it was undertaken by a consortium led by National Technical University of Athens (NTUA). The objective was to investigate the dynamics of DGs in microgrids and develop strategies for a number of issues such as control algorithms, protection schemes, black start strategies as well as definition of DG interface response and intelligence requirements [5]. A pilot installation was realized on the Kythnos Island, Greece. A comprehensive study on microgrid control methods was performed in ISET microgrid, Germany. The

continuation of the project was "More Microgrids Project" again undertaken by a consortium led by NTUA. This project was executed to study alternative methods, strategies along with universalization and plug-and-play concepts. The demonstration site is an ecological estate in Mannheim–Wallstadt, Germany [75].

Other implementations with smaller scales include the Labein Microgrid in Spain, Frielas Feeder in Portugal, CESI Microgrid in Italy, Continuon Holiday Camp Microgrid in the Netherlands, Am Steinwag Settlement in Germany [5,8,75].

4.2. Japan

Japan is committed to utilize RE systems, however this puts the country's well-earned high power quality reputation in jeopardy. The RE systems used in Japan are mostly wind turbines and PV systems, intermittent nature of which is an additional setback. Microgrid's ability to address these problems motivated the projects in Japan and hence the country has the most microgrid implementation projects worldwide [76]. Most of the projects are funded by the New Energy and Industrial Technology Development Organization (NEDO). Three demonstrations sites were installed in 2003 under NEDO's Power grid with renewable Energy Resources Project.

The first project started operation in 2005 World Exposition in Aichi although it is removed to Tokoname City near Nagoya in 2006. This system uses fuel cells, PV panels and NaS battery storage system. This microgrid is used to feed some major pavilions and it was put to test twice for independent operation in 2005 and 2007. Although the first test revealed some deficiencies in controlling the voltage and frequency, the second experiment was more successful [76]. The second demonstration site is in Kyotango where a biogas plant is connected to two PV systems and a small wind turbine. This network operates as a VPP and interestingly instead of the latest technology the communication is realized over conventional information networks such as ISDN and ADSL [5,8]. The third project in Hachinohe is being undertaken by the Mitsubishi Research Institute and Mitsubishi Electric [77]. This system has its private distribution line and consists of PV systems, wind turbines, gas engines and storage. The management scheme developed here ensures stability and meets building demands. An additional project has been started by NEDO in Sendai city where four levels of customer power will be studied. The system will have power quality backup system in order to reduce interruptions and voltage drops. This project is aimed at studying the possibility of supplying different service levels to customers in the same area. The system has enhanced the power quality since it was put into action in 2007 [6].

There are several private microgrid research projects. For example, the Shimizsu Microgrid is being developed by the Shimuzu Corporation with the cooperation of the University of Tokyo to develop an optimum operation and control system. Tokyo Gas on the other hand, again partnering with the University of Tokyo, is trying to develop an integrated DG control through simulations and experiments at its facility in Yokohama [6]. Crossing boundaries, Mitsubishi Corporation has installed a small grid in Hsinchiang, China and it can be supplied by distribution network, PV systems, battery storage and genset operation [78].

4.3. Korea

Korea's first and only pilot project is being developed by the Korean Energy Research Institute (KERI). The test system is very comprehensive as it includes several types of DGs such as PV simulator, fuel cells, diesel generators, wind turbine simulator along with significant and non-significant loads. The network is equipped with storage and power quality devices. An energy management system is being implemented which even takes weather conditions into account and communicates with the components through a gateway. Being equipped with rich mixture of components, the KERI microgrid is aimed at testing and studying almost all aspects of microgrids. The whole project was implemented in two phases where in the first phase, the microgrid was kept as a 100 kW class plant and in the second phase it was extended for further studies [79].

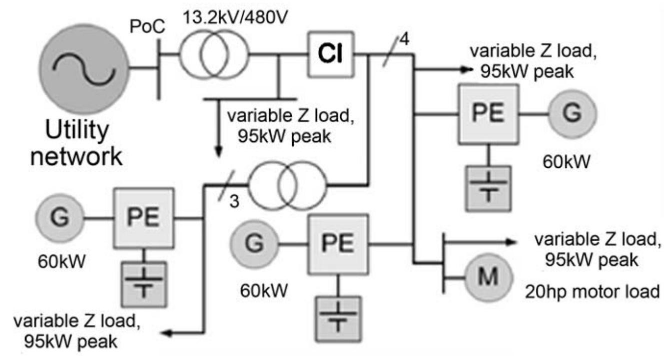

Fig. 5. CERTS microgrid [8].

Jeju Island is receiving increasing attention due to its immense potential for RE resources. The total wind power energy in Jeju was only 19 MW in 2006 and it has increased to 230 MW in 2009 whereas several fuel cell plants are either constructed or planned on the island [80]. Jeju Island and similar Korean islands are prime candidates for microgrid implementations in Korea in the future [81].

4.4. North America

CERTS (the Consortium for Electric Reliability Technology Solutions), shown in Fig. 5 [8], is the most well-known of U.S. microgrids. It is a collaboration between AEP, TECOGEN, Northern Power Systems, S&C Electric Co, Sandia National Laboratories and the University of Wisconsin [8]. It consists of several DGs and a thyristor based switch to allow isolation from the grid. The main objective of this research was to facilitate easy connection of small distributed generators to the network. As a result, three advanced concepts, also referred to as the CERTS microgrid concept, have been developed and demonstrated to decrease the field engineering work on microgrids. These concepts can be listed as a method to ensure automatic and seamless transition between grid connected and islanded modes, a protection method inside the microgrids which does not depend on high fault currents and a microgrid control scheme to stabilize system frequency and voltage without utilizing high speed communication [82].

Also, two software tools, which are required for microgrid deployment, are being developed in relation with CERTS project. These are μgrid Analysis tool (μGrid) developed by the Georgia Institute of Technology and the Distributed Energy Resources Customer Adoption Model (DER-CAM) in use at the Berkeley Lab [5].

There are other implementations going on in Mad River Waitsfield by Northern Power Systems, British Colombia Institute of Technology Microgrid and the General Electric Microgrid [8]. These systems are currently at R&D stage and the objective is to design control and protection strategies for different types of microgrids.

4.5. Australia

Currently, there are no microgrid pilot projects in Australia but there is a large potential, and with the Government's incentives, extensive research on distributed energy and microgrids has recently started. Australia is a very vast continent-country which

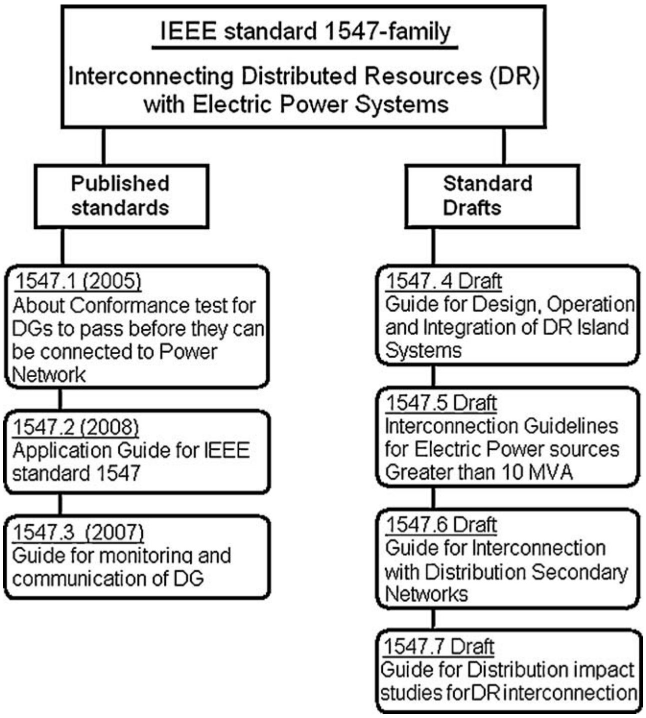

Fig. 6. IEEE SCC21 1547 series of interconnection standards.

has many isolated communities. It is a new trend in the Australian Electricity Market to utilize RE resources for local power generation and local consumption. Some of these communities are not only far away but also lack access roads to the weather conditions. Utilization of DGs and implementation of microgrids for that purpose will ease the transmission and distribution burden on service providers. The ultimate goal is to realize the design and provision of power station infrastructure which will be optimized to suit the unmanned status of the power stations. The Yungngora and Kalumburu communities in Western Australia [83], and the Windorah community in Queensland [84] are examples of such distant communities which are candidates for microgrid operations. In addition to this, some energy companies are trying to operate microgrids on islands such as Thursday Island in Queensland [84] and King Island in Tasmania [16].

5. Standards and universalization

DG offers numerous potential benefits including reduced electric line losses, reduced transmission and distribution congestion. Improved grid asset utilization, improved grid reliability, cleaner energy, voltage support, uninterrupted service can further be added to the list. However, this needs proper integration of DGs to the electric power systems since these systems are not designed to accommodate active generation and storage at the distribution level [85]. The evolution of DG was not pioneered by a single organization or a company rather every institution runs its own R&D project. As a result, there are many different types of DGs, interconnections, electronics interfaces. This makes it incredibly difficult to draft a set of rules/guidelines for DGs interconnection and utilization. Since microgrids are formed with DGs, the very concept of a microgrid and its wide acceptance are also paralyzed by this fact. In an effort to tackle this issue, there are several standardization and universalization works performed by several bodies. The ultimate objective is to standardize certain aspects of DGs and microgrids while there is no technology or design constraint stipulated to hinder the versatility of these concepts. Some of these standards, shown in Fig. 5, are in force while others are still in drafting phase.

The first standard prepared was about the rules governing the connection of DGs to the electric power system. For a DG to be connected to the grid, it has to conform with requirements of IEEE Standard 1547.1 [45]. Only for this purpose, an alternative standard UL 1741 [44] can also be used. Both standards require that in the case of islanding, all DGs shall be disconnected from the islanded microgrid. This does not take full advantage of DGs nor is it possible to conform with this requirement if islanded operation is desired [69]. For this reason, another part to the IEEE Standard 1547, namely 1547.4, is being drafted which focuses on integration of islanded systems with the utility. The part 1547.4 is being treated as one of the fundamental standards to play a key role for microgrid standardization as it covers vital planning and operating aspects such as impacts of voltage, frequency, power quality, protection schemes and modifications, the characteristics of the DER, reserve margins, and load shedding. The part 1547.3 is about monitoring and communication of DGs. Its purpose is to facilitate the interoperability of DGs in an interconnected system.

IEEE Standard Coordinating Committee 21 (SCC21) is well aware of the developments in the electricity sector and it constantly supports the development of new standard drafts. Initially, IEEE 1547 standard covered DGs with capacity less than 10 MVA [85]. However, with the recent developments in technology, there are systems with larger capacities. The draft standard 1547.5 is aimed at preparing guidelines for such systems which are not covered by the IEEE 1547.1. The draft standard 1547.6 considers interconnection of distribution secondary network system types of area electric power systems (Area EPS) with DG. 1547.7 is a very significant step towards standardization and universalization in microgrids and DGs. It covers the necessary methodology, testing steps and aspects to assess the impact of a DG on the system. This study will be helpful for network operators, contractors, and regulatory bodies to understand the impact of a particular DG on the network after connection.

In a larger scale than that of the 1547.7 draft, a "Microgrid Citizenship Tool" is proposed in [1] to evaluate how a microgrid will appear to the grid. This tool assesses a microgrid's good citizenship level based on the three key characteristics: generation capacity, installed storage and load. A microgrid is classified as a good citizen if it contributes to the performance of the grid with a consistent profile whereas a microgrid with high transient and unpredictable variations will represent a bad citizen. Such a method may be utilized in electricity market as a useful tool to estimate the impact of a microgrid on the network. If a standard methodology is developed, such a concept will be an indispensible part of standardized microgrid assessment and planning process.

National Renewable Energy Laboratory (NREL) conducted research on interconnection, grid effects and tariff design for DERs and one of the areas was "Advanced Universal Interconnection Technology". It is believed that universalized interconnection DGs will facilitate the connection with EPS [67]. The objective is to design a modular interface device which will respond the power electronics requirements of any DG system and provide interconnection interface in a safe, reliable and cost effective manner. A prototype was developed by the Northern Power Systems (NPS) which manages power management, conditioning and relaying functions with a DSP-based architecture. It was designed to be compatible with different circuit breakers, switching technologies, RE based DGs and conventional generators [86]. The research outcomes were promising and a new design with cost reduction as the primary objective is planned.

As outlined in the preceding sections, there is a growing interest in extensive communication for network management, control and

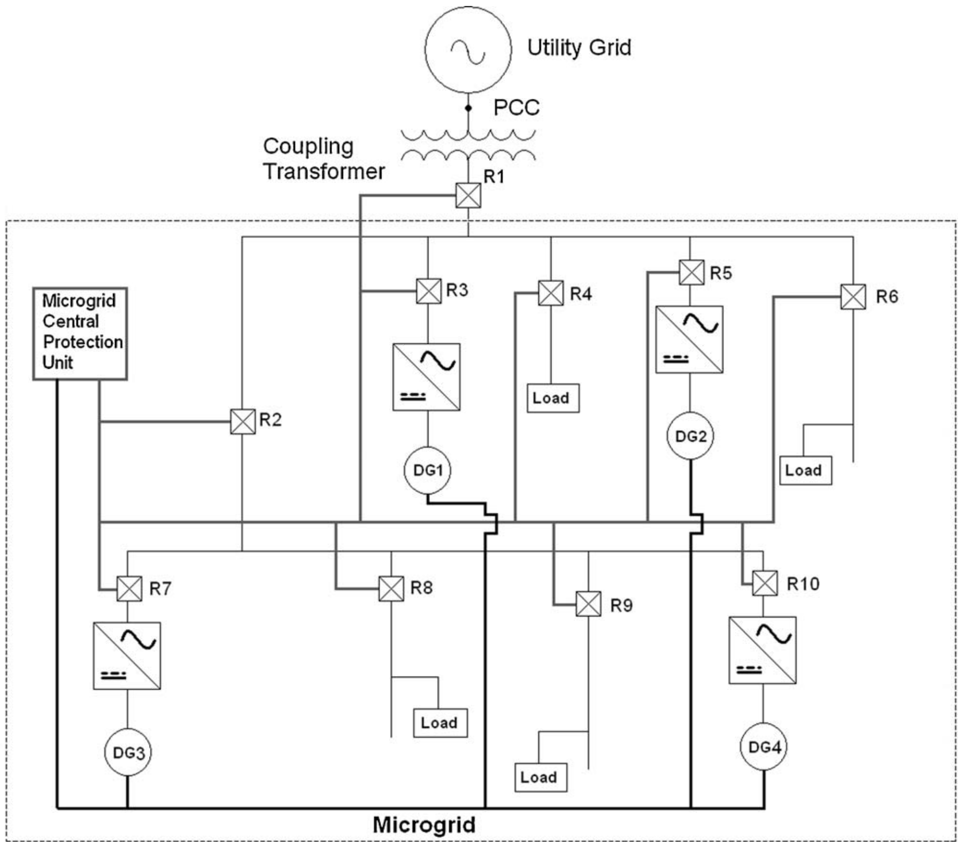

Fig. 7. A centralized protection scheme with communication.

protection purposes. However, there is no consensus in the literature about which communication protocol shall be used in these systems. It is known that communication devices and systems will add to the complexity of microgrids and this may constitute some problems. For this reason, worldwide collaboration is required in identifying a universal or standardized communication protocol that shall be used in microgrids for DGs, storage and protection devices to tackle the arising problems. IEC 61850 was released in 2003 for the first time for a communication within a substation automation system, yet it has been used for other purposes [87]. With a vision of controlling DGs it has been extended. The first release, IEC 61400-25 was about the communication in wind power [66]. Two more extensions IEC 61850-7-410 on hydroelectric power plants and IEC 61850-7-420 on DERs logical nodes have also been published. These two extensions might be used in designing the communication system of DGs in detail.

6. Future work and possible research areas

Microgrid is a very exciting research field in the power engineering and it has many different aspects which are considered as individual research fields in their own. Furthermore, microgrids are just like an intersection zone of several concepts such as network operations, protection, power electronics, distributed generation, renewable energy etc. Consequently, it is not a surprise to see more researchers focusing on microgrids and more publications appearing in the literature. It is safe to assume that this field will continue to expand in the future. When the literature is sifted, it is noticed that considerable amount of attention has been given to some aspects of the microgrid, while others are left untouched either because they simply did not exist before or gained importance recently. Whatever the reason, the possible future research areas are mostly under these topics.

Microgrid energy management systems (MEMS) which are aimed at controlling the microgrid in a holistic sense are fairly new in the literature. Although the very concept of MEMS is proposed some time ago, real design and implementations of MEMS are crucial to get more knowledge and experience in the field. Conceptual designs look appealing but implementations or simulations on models shall be carried out to see the real side of the picture.

Protection of microgrids against fault currents and design of new protection schemes are also promising research fields. Similar to above, there are conceptual designs or proposed opinions in the literature while it is hard to find a new protection design in a microgrid which responds to the needs of microgrid operation modes and components. There are proposals to change the relay types used or update their operating currents regularly or redesigning the protection techniques from scratch. Fig. 6 shows a new protection system proposed by the authors.

This protection scheme employs communication between a central protection unit and protection devices and DGs. According to the conceptual design, operating points of relays are continuously updated in parallel with the changes occurring in the system (Fig. 7).

Despite of these several proposals, there is lack of implementation in the literature. All of these alternative protection schemes proposed in the literature shall be implemented/modeled to see the feasibility and the performance of the proposals.

Unlike traditional utility networks, it is highly probable that microgrids will incorporate high speed communication between the components, operators, equipments etc. However, there is obscurity on how to realize the communication, what type of an

infrastructure is needed, what types of protocols shall be used. Doubtlessly, some additional work is needed to clarify these details as well.

For microgrids to be embraced rapidly and implemented easily, there is a need for systematic standardization and universalization in all aspects of this field. This would not only help in bringing different organizations together but also encourage more people to accept transition to microgrid. If standard procedures are implemented and universalized components/interfaces are utilized instead of re-inventing the wheel for every single microgrid project, past experiences can easily be put into practice.

7. Conclusion

The world we live in today is being troubled by the concerns on global warming, pollution and CO_2 emissions. RE systems offer means of generating cleaner and sustainable energy. However, there are lots of challenges that must be tackled so that RE resources could be utilized to their full potential. RE resources are mostly dispersed and different generation approaches should be used to harvest the maximum potential out of those sources. This is contradictory to the traditional concept of central generation and distribution over large distances. For this reason, existing grids are not entirely compatible for excessive integration of DG units. On top of that, micro-scale implementation of known generation plants such as micro hydroelectric power plants, diesel generators and etc., have similar aspects since they are also distributed and their generation capacities are much smaller than their traditional giant counterparts.

In order to achieve a cleaner, reliable, and secure power generation, transmission and distribution system, the various challenges brought about by this new grid structure and management system shall be tackled with similar research projects. The outputs of studies on microgrids will aid in the development of secure, reliable, and stable real-life networks with greater penetration of RE sources. This will aid in achieving a more reliable, secure and cleaner energy without compromising from environment protection and similar concepts.

This paper has presented the current status of the literature on microgrid related research. It has described the microgrid concept and the motivations behind its utilization then outlined the different research fields under this heading. The undergoing research work was summarized to give an overall insight about the current level of the knowledge. Finally, possible research areas have been proposed which are essential for future development.

References

[1] Colson CM, Nehrir MH. A review of challenges to real-time power management of microgrids. In: Power & Energy Society General Meeting, 2009, PES '09. IEEE. 2009. p. 1–8.
[2] Kroposki B. et al, Renewable Systems Interconnection - Executive Summary, Technical Report, National Renewable Energy Laboratory, NREL/TP-581-42292, February 2008.
[3] Currie RAF. Fundamental research challenges for active management of distribution networks with high levels of renewable generation. In: Universities Power Engineering Conference, 2004. UPEC 2004, 39th International, vol. 2. 2004. p. 1024–8.
[4] Boutsika T. Calculation of the fault level contribution of distributed generation according to IEC Standard 60909. In: Presented at the Proc. CIGRE Symposium Athens, April. 2005.
[5] Hatziargyriou N. Microgrids. Power and Energy Magazine, IEEE 2007;5:78–94.
[6] Kroposki B. Making microgrids work. Power and Energy Magazine, IEEE 2008;6:40–53.
[7] Peng FZ, Li YW, Tolbert LM. Control and protection of power electronics interfaced distributed generation systems in a customer-driven microgrid. In: Presented at the Power & Energy Society General Meeting, PES '09. IEEE. 2009.
[8] Mike BARNES. Real-world microgrids – an overview. In: Presented at the IEEE International Conference on System of Systems Engineering. 2007.
[9] Lasseter B. Microgrids [distributed power generation]. In: Power Engineering Society Winter Meeting, 2001. IEEE, vol. 1. 2001. p. 146–9.
[10] Xialing X, Xiaoming Z. Overview of the researches on distributed generation and microgrid. In: Power Engineering Conference, 2007. IPEC 2007. International. 2007. p. 966–71.
[11] Sudipta C. Distributed intelligent energy management system for a single-phase high-frequency AC microgrid. IEEE Transactions on Industrial Electronics 2007;54:97–109.
[12] Komatsu K. New IGBT modules for advanced neutral-point-clamped 3-level power converters. In: International Power Electronics Conference (IPEC), 2010. 2010. p. 523–7.
[13] Zhang QJ. SiC Power Devices for Microgrids. IEEE Transactions on Power Electronics 2010. pp. 2889–96.
[14] Divya KC, Østergaard J. Battery energy storage technology for power systems—an overview. Electric Power Systems Research 2009;79:511–20.
[15] Arai J. Power electronics and its applications to renewable energy in Japan. Circuits and Systems Magazine, IEEE 2008;8:52–66.
[16] HydroTasmania, King Island Renewable Energy Integration Project, CEIC, Storage Tech Clinic, February 2010.
[17] www.llyoldenergy.com/heatstorage.htm, Llyold Energy Corporate Website.
[18] Katiraei F. Microgrids management. Power and Energy Magazine, IEEE 2008;6:54–65.
[19] Sung-Woo P. Control schemes of the inverter-interfaced multi-functional dispersed generation. In: Power Engineering Society General Meeting, 2003, IEEE, vol. 3. 2003. p. 1924–9.
[20] Katiraei F. Micro-grid autonomous operation during and subsequent to islanding process. IEEE Transactions on Power Delivery 2005;20:248–57.
[21] Diaz G. Scheduling of droop coefficients for frequency and voltage regulation in isolated microgrids. IEEE Transactions on Power Systems 2010;25:489–96.
[22] Chandorkar MC. Control of parallel connected inverters in standalone AC supply systems. Industry Applications, IEEE Transactions on 1993;29:136–43.
[23] Soultanis NL. A stability algorithm for the dynamic analysis of inverter dominated unbalanced LV microgrids. IEEE Transactions on Power Systems 2007;22:294–304.
[24] Il-Yop C. Control methods of inverter-interfaced distributed generators in a microgrid system. IEEE Transactions on Industry Applications 2010;46:1078–88.
[25] Borup U. Sharing of nonlinear load in parallel-connected three-phase converters. IEEE Transactions on Industry Applications 2001;37:1817–23.
[26] Hernandez-Aramburo CA. Fuel consumption minimization of a microgrid. IEEE Transactions on Industry Applications 2005;41:673–81.
[27] Pogaku N. Modeling, analysis and testing of autonomous operation of an inverter-based microgrid. IEEE Transactions on Power Electronics 2007;22:613–25.
[28] Roy MM. The electrical characteristics and selection of low-voltage power cables. Power Engineering Journal 1987;1:239–44.
[29] De Brabandere K. A voltage and frequency droop control method for parallel inverters. IEEE Transactions on Power Electronics 2007;22:1107–15.
[30] Bianchi FD. Optimal gain-scheduled control of fixed-speed active stall wind turbines. Renewable Power Generation, IET 2008;2:228–38.
[31] Barklund E. Energy management in autonomous microgrid using stability-constrained droop control of inverters. IEEE Transactions on Power Electronics 2008;23:2346–52.
[32] Coelho EAA. Small signal stability for single phase inverter connected to stiff. In: Industry Applications Conference, 1999 Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE, vol. 4. 1999. p. 2180–7.
[33] Guerrero JM. A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems. IEEE Transactions on Power Electronics 2004;19:1205–13.
[34] Chiang SJ. A multimodule parallelable series-connected PWM voltage regulator. IEEE Transactions on Industrial Electronics 2001;48:506–16.
[35] Sao CK, Lehn PW. Intentional islanded operation of converter fed microgrids. In: Power Engineering Society General Meeting, 2006 IEEE. 2006. p. 6.
[36] Engler A, Soultanis N. Droop control in LV-grids. In: 2005 International Conference on Future Power Systems. 2005. pp. 1–6.
[37] Sao CK, Lehn PW. Control and power management of converter fed microgrids. IEEE Transactions on Power Systems 2008;23:1088–98.
[38] Guerrero JM. Wireless-control strategy for parallel operation of distributed-generation inverters. IEEE Transactions on Industrial Electronics 2006;53:1461–70.
[39] Guerrero JM. Decentralized control for parallel operation of distributed generation inverters using resistive output impedance. IEEE Transactions on Industrial Electronics 2007;54:994–1004.
[40] Seon-Ju A. Power-sharing method of multiple distributed generators considering control modes and configurations of a microgrid. IEEE Transactions on Power Delivery 2010;25:2007–16.
[41] Lopes LAC, Yongzheng Z. Islanding detection assessment of multi-inverter systems with active frequency drifting methods. IEEE Transactions on Power Delivery 2008;23:480–6.
[42] Abdolrasol MGM, Mekhilef S. Hybrid anti-islanding algorithm for utility interconnection of distributed generation. In: 2009 International Conference for Technical Postgraduates (TECHPOS). 2009. p. 1–5.
[43] Walling RA, Miller NW. Distributed generation islanding-implications on power system dynamic performance. In: Power Engineering Society Summer Meeting, 2002 IEEE, vol. 1. 2002. p. 92–6.
[44] UL-1741, Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources, ed., 2002.

[45] IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems, IEEE Std 1547-2003, pp. 0_1-16, 2003.
[46] IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic (PV) Systems, ANSI/IEEE Std 929-1988, p. 0_1, 1987.
[47] Redfern MA. A new microprocessor based islanding protection algorithm for dispersed storage and generation units. IEEE Transactions on Power Delivery 1995;10:1249–54.
[48] Wen-Jung C. Novel active islanding detection method for distributed power generation system. In: International Conference on Power System Technology, 2006. PowerCon 2006. 2006. p. 1–7.
[49] Conti S, Raiti S. Integrated protection scheme to coordinate MV distribution network devices. DG interface protections and micro-grids operation. In: International Conference on Clean Electrical Power, 2009. 2009. p. 640–6.
[50] Bower W, Ropp M. Evaluation of islanding detection methods for photovoltaic utility-interactive power systems. Sandia National Laboratories Photovoltaic Systems Research and Development 2002.
[51] Benato R, Caldon R. Distribution Line Carrier: Analysis Procedure and Applications to DG. In: Transmission and Distribution Conference and Exhibition, 2005/2006 IEEE PES. 2006. p. 1177–84.
[52] Barker PP, De Mello RW. Determining the impact of distributed generation on power systems I. Radial distribution systems. In: Power Engineering Society Summer Meeting, 2000. IEEE, vol. 3. 2000. p. 1645–56.
[53] A. Oudalov and A. Fidigatti, Adaptive Network Protection in Microgrids, More Microgrids Europe www.microgrids.eu/documents/519.pdf.
[54] Wu CX. The existed problems and possible solutions of micro-grid based on distributed generation,. In: Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 2008, DRPT, 2008. 2008. p. 2763–8.
[55] Baran ME, El-Markaby I. Fault analysis on distribution feeders with distributed generators. IEEE Transactions on Power Systems 2005;20:1757–64.
[56] Marnay C. Shape of the microgrid. In: Power Engineering Society Winter Meeting, 2001, IEEE, vol. 1. 2001. p. 150–3.
[57] Kueck JD. Microgrid energy management system. In: Oak Ridge National LaboratoryJan. 2003.
[58] Hussain B. Integration of distributed generation into the grid: protection challenges and solutions. In: Managing the Change 10th IET International Conference on Developments in Power System Protection (DPSP 2010). 2010. p. 1–5.
[59] Laaksonen H. Protection Principles for Future Microgrids. IEEE Transactions on Power Electronics 2010. pp. 2910–18.
[60] Salomonsson D. Protection of low-voltage DC microgrids. IEEE Transactions on Power Delivery 2009;24:1045–53.
[61] Shuiming C, Hongqiao Y. A review on overvoltages in microgrids. In: Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific. 2010. p. 1–4.
[62] Vilathgamuwa DM. Protection of microgrids during utility voltage sags. IEEE Transactions on Industrial Electronics 2006;53:1427–36.
[63] Vieira JCM. Performance of frequency relays for distributed generation protection. IEEE Transactions on Power Delivery 2006;21:1120–7.
[64] Zeineldin HH. Protective relay coordination for micro-grid operation using particle swarm optimization. In: 2006 Large Engineering Systems Conference on Power Engineering. 2006. p. 152–7.
[65] Conti S. Analysis of protection issues in autonomous MV micro-grids. In: 20th International Conference and Exhibition on Electricity Distribution – Part 1, 2009, CIRED 2009. 2009. p. 1–5.
[66] Timbus A. Integration of wind energy resources in the utility control and information technology infrastructures. In: IEEE International Symposium on Industrial Electronics, 2008, ISIE 2008. 2008. p. 2371–6.
[67] Piagi P, Lasseter RH. Autonomous control of microgrids. In: Power Engineering Society General Meeting, 2006, IEEE. 2006. p. 8.
[68] Yingyuan Z. Study of energy management system for distributed generation systems. In: Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 2008, DRPT, 2008. 2008. p. 2465–9.
[69] Ming D. Key technologies for microgrids – a review. In: International Conference on Sustainable Power Generation and Supply, 2009, SUPERGEN '09. 2009. p. 1–5.
[70] Dimeas AL, Hatziargyriou ND. Operation of a multiagent system for microgrid control. IEEE Transactions on Power Systems 2005;20:1447–55.
[71] Dielmann K, van der Velden A. Virtual power plants (VPP) – a new perspective for energy generation? Modern Techniques and Technologies, 2003. MTT 2003. Proceedings of the 9th International Scientific and Practical Conference of Students, Post-graduates and Young Scientists. 2003. p. 18–20.
[72] Weaver WW, Krein PT. Game-theoretic control of small-scale power systems. IEEE Transactions on Power Delivery 2009;24:1560–7.
[73] Colson CM. Ant colony optimization for microgrid multi-objective power management. In: Power Systems Conference and Exposition, 2009, PSCE '09. IEEE/PES. 2009. p. 1–7.
[74] Imolauer K. Market and business chances in the EU in the field of renewable energies and energy efficiency. In: 29th International Telecommunications Energy Conference, 2007, INTELEC 2007. 2007. p. 477–80.
[75] Buchholz B. Long term European field tests for microgrids. In: Power Conversion Conference – Nagoya, 2007. PCC '07. 2007. p. 643–5.
[76] Morozumi S. Micro-grid demonstration projects in Japan. In: Power Conversion Conference - Nagoya, 2007. PCC '07. 2007. p. 635–42.
[77] Morozumi S. Overview of microgrid research and development activities in Japan. In: Presented at the International Symposium on Microgrids, Montreal, June. 2006.
[78] T. Goda, Microgrid Research at Mitsubishi, California Energy Commission Symposium, http://www.energy.ca.gov/research/esi/documents/2005-06-17_symposium/GODA_2005-06-17.PDF, June 2006.
[79] Keeyoung N. Establishment of a pilot plant for KERI microgrid system based on power IT development program in Korea. In: Transmission & Distribution Conference & Exposition: Asia and Pacific, 2009. 2009. p. 1–6.
[80] Lee KY, Se Ho K. Progress in distributed generation in Korea. In: Power Engineering Society General Meeting, 2007, IEEE. 2007. p. 1–6.
[81] Choi J. Overview of microgrid research and development in Korea. In: Presented at the Communities for Advanced Distributed Energy Resources. 2009.
[82] Eto J. Overview of the CERTS microgrid laboratory test bed. In: Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium, 2009. 2009. pp. 1–8.
[83] Fox TH. CEIC energy storage. In: Off-Grid Tech Clinic Horizon Power. 2010.
[84] Gabriel B. Energy storage techclinic. In: Presented at the Off-Grid Tech Clinic, Ergon Energy. 2010.
[85] Basso TS, DeBlasio R. IEEE 1547 series of standards: interconnection issues. IEEE Transactions on Power Electronics 2004;19:1159–62.
[86] J. Lynch, et al. Flexible DER utility interface system: final report September 2004–May 2006, National Renewable Energy Laboratory September 2006.
[87] Brunner C. IEC 61850 for power system communication. In: Transmission and Distribution Conference and Exposition, 2008, IEEE/PES. 2008. p. 1–6.

Taha Selim USTUN received his B.E. degree in Electrical and Electronics Engineering from Middle East Technical University, Turkey in 2007 and the Master of Engineering Science degree from University of Malaya, Malaysia in 2009. He is currently a PhD student in Victoria University, Melbourne. His research interests are power systems, power electronics, distributed generation and microgrids.

Cagil Ozansoy received his B.Eng. degree in Electrical and Electronic Engineering (Hons.) from Victoria University, Melbourne, Australia in 2002. In 2006, he completed his PhD research degree in the area of power system communications. He is now working as a lecturer and researcher in the School of Engineering and Science, Victoria University. His major teaching and research focus is on electrical engineering, renewable energy technologies, energy storage, and distributed generation. He has successfully carried out and supervised many sustainability related studies in collaboration with local governments in the past. These include the assessment of solar and wind electric energy potential in Melbourne's west. He has over 25 publications detailing his work and contributions to knowledge.

Aladin Zayegh received his BE degree in Electrical Engineering from Aleppo University in 1970 and PhD degree from Claude Bernard University, Lyon, France in 1979. He has held lecturing position at several Universities and since 1991 he has been at Victoria University, Melbourne, Australia. He has been head of School and research director where he has conducted research, supervised several PhD students and published more than 250 Papers in peer reviewed International Conferences and Journals. He is currently Associate Professor at the School of Engineering and Science, Faculty of Health, Engineering and Science at Victoria University, Melbourne, Australia. His research interest includes Renewable energy, Embedded Systems, instrumentation, data acquisition and interfacing, Sensors and Microelectronics for Biomedical applications.